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A Publication of the Society of Economic Paleontologists and Mineralogists
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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 8, NO. 3, PP. 77–83, FIGS. 1–4, DECEMBER, 1938

ORIGINAL STRUCTURES IN COLORADO RIVER FLOOD DEPOSITS OF GRAND CANYON

EDWIN D. McKEE
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ABSTRACT

Original structures of distinctive character are developed during deposition of flood deposits along the Colorado River in Grand Canyon. A description of the types of bedding and cross-lamination in these deposits is given and a comparison is made between them and the original structures formed in certain other environments including the Colorado River delta and typical sea beaches. Two forms of contemporaneous deformation developed in Colorado River flood deposits are described and discussed.

INTRODUCTION

During the fall of 1937 while on a geological expedition through the Grand Canyon of Arizona, under auspices of the Carnegie Institution and the California Institute of Technology, the writer was able to make many observations and to record data on the nature of flood deposits which are annually developed at various places along the Colorado River, especially at the mouths of large tributary canyons. These data, together with material accumulated over a number of years in the Bright Angel quadrangle, serve to illustrate clearly the character of original structures developed under such flood conditions.

Inasmuch as the sedimentary and stratigraphic geologist is today greatly handicapped in attempts to interpret many formations because of a dearth of material on the character of bedding and cross-lamination developed under various environments, the recording of this type seems desirable. Only when such records have been made for many types and in many localities, can generalizations on the significance of original structures in sediments be developed and applied with assurance in geological studies.

Acknowledgments.—The writer is indebted to Drs. Ian Campbell and John Maxson of the California Institute of Technology and Dr. J. T. Stark of Northwestern University, his associates on a boat trip down the Colorado River, for many helpful suggestions and for constructive criticism of the manuscript. Permission to publish has been granted by the National Park Service and by the Carnegie Institution of Washington.

CHARACTER OF FLOODS AND FLOOD DEPOSITS

The Colorado River, in common with most streams rising in well-watered highlands and passing through desert regions, is notorious for its floods and for tremendous fluctuations. A maximum recorded discharge of 210,000 cubic feet per second in June 1921 and a maximum known flood (1884) for which the discharge was between 250,000 and 300,000 cubic feet per second (1), illustrate peaks which this river reaches. On the other hand, during the lowest stages the river may have a discharge of only 2,000 cubic feet or less, thus there are seasonal increases of one hundred fold. Likewise, detrital matter carried by the river fluctuates tremendously and varies in rate from "a few tons a day to more than a thousand tons per second" (2).

Many of the fluctuations in discharge along the Colorado River are extremely rapid. The river may rise many feet in a few hours, cover the narrow beaches on each side, and back into the mouths of

tributary canyons. It is at such times that the stream quickly deposits sediments in protected embayments, especially side canyons, and leaves stranded great quantities of silt and sand as its waters recede. In effect, it forms an "upper beach" in favorable places along the river, and, as might be expected, the sediment here is somewhat coarser than that in the "normal beach" which is formed by waters of lesser transporting power. Analyses of several average samples show flood deposits dominantly between 120–230 mesh size; those of normal deposits from the same locality dominantly between 60–120 mesh size.

Colorado River shore deposits form a beach consisting essentially of two parts: (1) that composed of beds sloping upward from the river, comparable to the foreshore beach (3) of a coastal region in that it is developed by waves and to some extent by currents; (2) that composed of horizontal deposits or ones which incline away from the river, comparable to the backshore beach in that it is formed by sheet floods spilling over the crest of the beach at high stage. Despite these general similarities between the river beach and that of a sea, the original structures developed in each differ decidedly. Ocean tides and continuous, rhythmic wave action are important factors influencing sea beach sedimentation, but these are notably lacking in river deposition. The latter shows far greater similarity in structure to a normal flood plain deposit and is, actually, a specialized type.

Foreshore and backshore deposits are recognized along the Colorado River not only in the "normal" beach formed when the river is at moderate stages, but also in the superimposed beach which is developed above and shoreward of the other during periods of sudden flood. Figures 1, 2 and 3 illustrate typical examples of this relationship as found in November 1937 at the mouths of Travertine, Separation, and Spencer Canyons. Although laminae in both beaches are probably of about the same type, only those in the upper or flood beach were analyzed in detail during this study. The sand in them invariably dries out soon after floodwaters recede, and original structures are then etched out by the wind; therefore, these deposits are adapted to easy examination.

TYPES OF ORIGINAL STRUCTURES

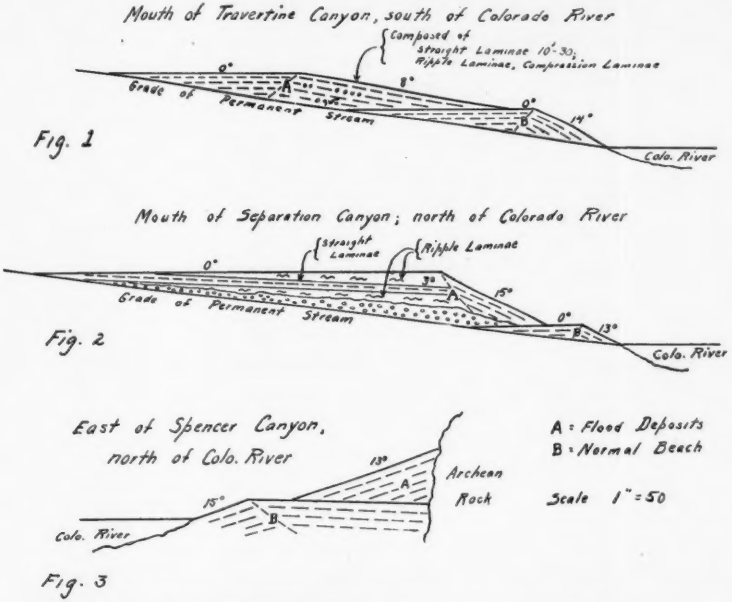
Shore structures developed in Colorado River flood deposits in Grand Canyon consist of two principal types. These are: (1) simple laminae developed by the deposition in identical manner of a series of smooth-surfaced sheets of sediment; (2) cross-lamination resulting from ripple-marks formed during deposition. Both types may be developed up a slope as in the foreshore beach, or on the level or down a slope as on the backshore beach. Scour and fill phenomena, although locally present, are not numerous.

The extent of any particular layer of deposits depends both on the space available (for the Canyon walls definitely restrict this), on the amount of detrital matter available for deposition at any particular time, and on the power of the transporting agent. In sections cut normal to the Colorado River course at the mouth of Travertine Canyon individual sloping laminae up to 130 feet long were found in the foreshore beach and up to 120 feet long in the horizontal beds of the backshore beach. At Separation Canyon measurements of corresponding features were 65 feet and 250 feet respectively. At the mouth of Walthenberg Canyon the backshore beach contained many laminae developed on planes which dipped away from the river at angles of 8 to 10 degrees and these laminae averaged around 7 feet in length.

The thickness of laminae seems to be controlled to a large extent by the coarseness of the sediment. In the upper or flood beaches at Separation and Spencer Canyons, counts showed averages of 14.5 (based on 6 counts) and 15 (9 counts)

laminae to the inch respectively, whereas in the finer sand of the lower or normal beaches at the same localities, the laminae averaged 25.5 (8 counts) and 24.5 (5 counts) to the inch. Counts at Walthenberg Canyon (upper beach) showed an average of 13.6 (10 counts) laminae to the inch and at Travertine Falls (lower beach) 22 (8 counts). The number 23 in the space of 1.25 inches, while on the crests the same number of laminae is concentrated into the space of 0.32 inch.

The cause of the development of laminae in these deposits is not definitely known except in a few places where it is obviously due to textural changes. Nowhere has change in composition ap-



FIGS. 1, 2, 3. Sections illustrating relationship between "normal" beach and superimposed flood-stage beach at three localities along Colorado River.

two rather definite classes into which these laminae resolve themselves are even more definite than the averages indicate, for the extremes of each grade are close to the average number and the maximum of the small size does not exceed the minimum of the other. In many of the ripple laminae, of course, concentration of detrital material fluctuates with crests and troughs of the ripples. This is illustrated by certain ripple laminae at Dubendorff which in troughs peared as a factor. Examination of thin section tends to confirm this view. Films of salts which develop crusts on the sand surfaces, as observed in fresh deposits, are thought to be important in this development and slight compaction of individual laminae, seen in thin section, may also be a factor.

RIPPLE CROSS-LAMINATION

Cross-lamination developed from asymmetrical water current ripples is not

only the most abundant type of structure in the Colorado flood deposits of Grand Canyon but is also the most diagnostic feature of such deposits. The ripple marks in most places range in wave length between 2.75 and 4 inches, but in the mouth of Separation Canyon somewhat larger ones, 4.5 to 6.75 inches, were found prevalent. Ripple indices measured in five localities showed low ratios, varying between 1:4 and 1:13, which is normal for water ripples. In some sections the indices are consistently greater than in others, but this is due, in part at least, to differences in the angle at which a section cuts the direction of ripple movement.

A classification of ripple cross-lamination has been proposed by the writer in a paper dealing with Colorado delta structures (4). Most of the types recognized there are also found in the Colorado River flood deposits in Grand Canyon. Many of the commonest in the one area, however, are rarest in the other, and vice versa. Laminae superimposed in rhythm and with uniform deposition (fig. 4A, B) are abundant in the canyon sections; likewise laminae showing lee-side concentration of sediment, with the characteristic pseudo-bedding that accompanies this type, are well represented (fig. 4C); but the complex patterns developed by laminae superimposed out of rhythm, which are so characteristic of deposits in the upper portion of the delta, are notably scarce.

The contrast between laminae in the Colorado delta sediments and those of flood deposits of Grand Canyon is largely a matter of the proportion of each type of ripple cross-lamination represented. This undoubtedly is due to the inconsistency of the depositing agents on the delta as compared with those responsible for the flood deposits in Grand Canyon. In the wide flat terrane which is the surface of the Colorado delta, changes in direction and speed of current are continuous and great. Within the narrow confines of Grand Canyon, however, where deposition is only possible in quiet sheltered embayments out of reach of the destructive force of the main river currents, sedimentation is rapid and takes place with relatively little chance for abrupt changes in the controlling forces.

REWORKING OF DEPOSITS BY WIND

In a majority of the river flood deposits in Grand Canyon, surfaces are constantly altered by wind. As soon as the sediment becomes dry, wind ripples with low crests and high indices are developed in many places. These are in marked contrast with the smaller water-made ripples of low index whose profiles form the intricate cross-lamination patterns exposed in sections of the underlying deposits. No evidence has been found to indicate that these wind ripples, found in dry surface sand, are preserved as a part of the deposit even when buried by additional material. A possible explanation for this failure of structures to be preserved is the lack of salt crusts such as are developed on each lamination in the case of water-laid deposits.

Inasmuch as there is a superficial resemblance between stream ripple development as found in many parts of the flood deposits and that caused by wind in reworking these deposits, a list of criteria which serve to illustrate the water-laid character of the former is given:

1. In some localities these beds contain pebbles and cobbles in laminae at various horizons among the ripple structures.
2. At the mouths of various side canyons remnants of these deposits are found clinging to walls on each side of permanent streams which have obviously cut through the centers.
3. These deposits have not been found above the levels of flood waters.
4. Ripple indices are invariably less than 1 to 16.
5. Compression laminae of types which could not be developed in dry sand are found locally in these deposits.

CONTEMPORANEOUS DEFORMATION

The desirability of being able to recognize among faults and folds those which have been developed in unconsolidated sediments has been pointed out by Nevin (5) and the importance of recording additional data on this subject is obvious. For these reasons, examples of contemporaneous deformation found in the Colorado River flood deposits of Grand Canyon are illustrated and described even though they are of local character and limited extent.

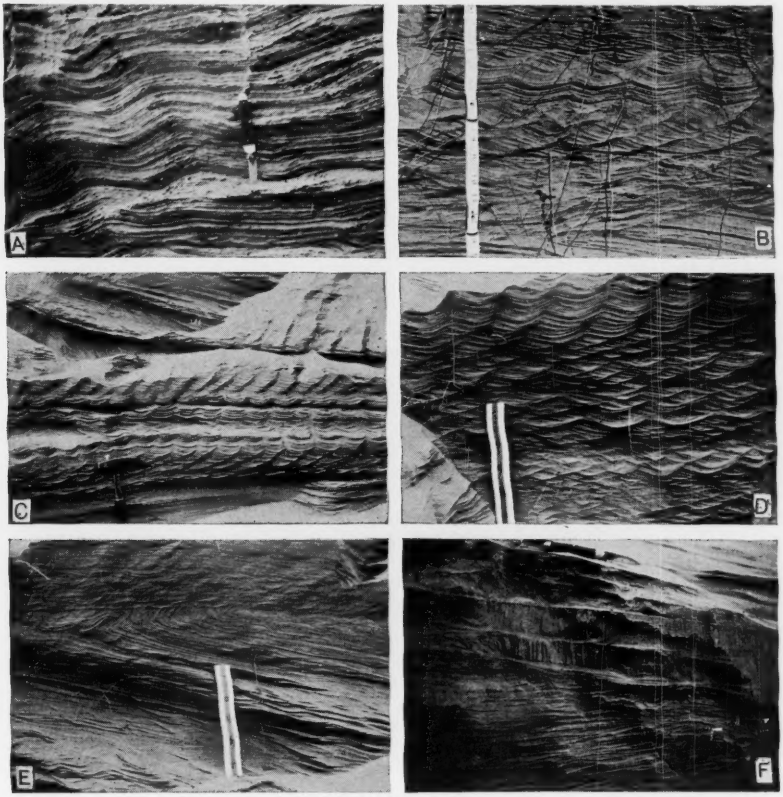


FIG. 4, A, B. Ripple laminae superimposed in rhythm and with uniform deposition, at Dubendorff Rapids (A) and at the mouth of Separation Canyon (B). C, D, Ripple laminae showing lee-side concentration of sediment with consequent development of pseudo-bedding, 123.5 mile canyon. E, F, Contemporaneous deformation in flood deposits at 123.5 mile canyon (E) and at Travertine Canyon (F).

At 123.5 mile canyon, north of Diamond Butte, and in Travertine Canyon, contemporaneous deformation in sand deposits has been noted. At the former locality, laminae of the backshore

beach, dipping away from the river, are in one place compressed into small tight folds inclined away from the source of the detrital material (fig. 4E). In the deposit in Travertine Canyon, on the other hand, local but complicated folding appears in laminae of the foreshore beach which dip toward the river (fig. 4F). Both examples of deformation are characterized by erosion surfaces that bevel the folded laminae, by a lack of fuzziness in the structure, by absence of cavities, by the small scale and local character of the deformation, and by the lack of disturbance of underlying laminae.

The principal conditions under which flexures, as contrasted with faults, are formed in unconsolidated sediments, are, according to Nevin (5, p. 182), when stresses are continued over a considerable time and when the sediment is fairly plastic. Knowledge of the conditions of deposition of the Colorado River deposits precludes the former explanation, in so far as they are concerned. Plasticity of beds alone, therefore, probably explains their deformation.

Lack of fuzziness in the folded laminae of the Colorado flood deposits suggests another factor in the development of these structures. It indicates quite clearly that the folding occurred after the water which deposited the sediment had drawn off. Rettger (6) has shown by experiment that force applied to unconsolidated sediments under water, and also to those out of water for only twenty minutes, results in structures which have fuzzy outlines, whereas the same pressures applied to sediments which have been out of water for twenty-four hours give structures with sharp definition.

The principal processes that have been suggested in explanation of contemporaneous deformation of sediments are subaqueous slump and differential movement. These are similar and overlapping in nature, therefore the characteristics which they develop in sediments are not always distinctive; nevertheless, Rettger (6, p. 282) has been able to demonstrate by experiment that certain criteria usually characterize a particular type. Folding which results from differential movement, for instance, is usually more regular than that formed by slump and the latter is very frequently bevelled across the top.

The illustration of folding at 123.5 mile canyon (fig. 4E) shows those characteristics that have been attributed to slumping. Furthermore, field evidence indicates that slumping was the process involved, for the movement of sediment during deposition, hence the force or load, was from the direction of dip of the axial planes and was down a sloping surface. Structures with almost identical appearance, but on a far greater scale, have been recorded from the Casper formation of Wyoming and explained by Knight (7) as due to "material of the oversteepened . . . side of the trough . . . [creeping] downward." He gives evidence that folding "was most intense on the side of the trough from which the stress was applied, and caused overturning away from the direction of stress application." These conditions are identical to those which occurred in the Colorado flood deposits.

An example of contemporaneous deformation, the details of which are difficult to explain, is at Travertine Canyon. Here two individual layers, each several centimeters thick, show the results of compressive forces. Some of the laminations within each have a nearly vertical attitude (fig. 4F) and represent the lower limbs of truncated folds. Obviously the top of each layer is a plane of erosion. Beds above and below the deformed ones are undisturbed.

In the compressed beds at Travertine Canyon evidence bearing on the direction from which force was exerted is contradictory. The upper bed shows the type of structure to be expected as a result of advancing water and sediment coming upslope from the river. Warped laminae are concave downward on the lower or near-river side with the lower limb of

each lamina becoming more nearly vertical and longer with distance upslope until finally, beyond the reach of maximum stress, only the upper limb of each lamina is affected, thus forming structures that are concave upward. In contrast to the upper deformed layer, however, the lower one shows opposite directions of folding and of concavity in those laminae which border the vertical ones. This suggests that force was exerted from the load above the deposits, rather than from the advancing flood waters.

Whatever the explanation may be, the results of this type of contemporaneous deformation are sufficiently interesting to merit being placed on record.

CONCLUSIONS

The description and analysis of original structures in Colorado River flood deposits are presented in this paper in order that criteria of this particular type of environment may be on record. The writer makes no claim to great geological importance for this type of deposit because of its usual lack of permanency and because of limited area of its distribution. A knowledge of its character is, nevertheless, important for purposes of comparison with the structures of other environments and for the inferences which may be drawn from it concerning the character of flood deposits at river mouths and in certain other extensive fluviatile deposits.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 8, NO. 3, PP. 84–90, FIGS. 1–3, TABLES 1–2, DECEMBER, 1938

SIZE FREQUENCY DISTRIBUTIONS OF SEDIMENTS AND THE NORMAL PHI CURVE

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ABSTRACT

The substitution of a logarithmic variable in the Gaussian function yields a logarithmic probability law (the normal phi curve) which has all the geometrical properties of the conventional normal law. That is, it is bell-shaped and symmetrical about its mean value, and it is completely described by two parameters, the phi mean and the phi standard deviation. Simple analytic and graphic methods are described for testing data for normalcy. Finally, some of the theoretical implications of normal phi curves are given, in terms of environmental factors which may control them.

INTRODUCTION

Among the more important functions in mathematical statistics is the probability curve, also referred to as the Gaussian curve, the normal curve of error, and the normal frequency curve. This curve finds wide application in theoretical and applied statistics, as well as in astronomy, physics, and other sciences. The function may be expressed in various ways; in terms of the ordinate y and the independent variable x, it is:

$$y = \frac{1}{\sigma_x\sqrt{2\pi}} e^{-(x-M_x)^2/2\sigma_x^2} \qquad 1$$

where M_x is the arithmetic mean of the x-values, and σ_x is their standard deviation. This curve is bell-shaped and symmetrical about its mean value, M_x.

When the variable x is chosen as diameter in mm., as in the treatment of sedimentary data, the plotted size frequency curves are almost invariably highly skewed. The normal curve of equation 1 thus finds little direct application in describing the size attributes of sediments. It has long been known, however, that the curves become much more symmetrical when plotted on a logarithmic size scale. The suggestion is strong that logarithmic frequency laws, rather than the Gaussian law, underlie these functions.

Logarithmic probability functions have been recognized for some time by mathematical statisticians, but frequently the expressions are considerably more tedious to handle than the normal law. Loveland and Trivelli (1927), working with the size frequency distributions of particles in photographic emulsions, reviewed the subject thoroughly, and concluded that ordinary moment analysis is not applicable. Hatch and Choate (1929) subsequently utilized logarithmic probability paper to test for logarithmically symmetrical data, and developed graphical methods for determining the log geometric mean size and the log standard geometric deviation.

The present writer (Krumbein, 1936) sought to avoid the complexities of direct logarithmic functions, and yet to retain the advantages of an analytic rather than a graphic approach. By the simple expedient of substituting a different variable directly into the *form* of equation 1, a normal law was developed having all the geometrical properties of the original, and retaining the essential simplicity of its analytic expression. The underlying theory involves merely the substitution of a logarithm, ϕ, for the diameter in mm., ξ, such that

$$\phi = -\log_2\xi. \qquad 2$$

The new variable, ϕ, its arithmetic mean, M_ϕ (the phi mean), and its standard deviation, σ_ϕ (the phi standard devia-

tion), were substituted directly into the form of equation 1, with the result that the normal phi curve was defined as follows:

$$y = \frac{1}{\sigma_\phi \sqrt{2\pi}} e^{-(\phi - M\phi)^2/2\sigma\phi^2}. \qquad 3$$

From the nature of equation 3 it is obvious that every property of equation 1, in terms of the variable x, is present in equation 3 in terms of the variable ϕ. This relation between the two functions means that the normal phi curve may be treated exactly as the Gaussian curve, except that the properties of the curve apply to a logarithm of the diameter instead of to the diameter itself.

The foregoing important characteristic of the normal phi curve should be emphasized. The function applies to the independent variable ϕ only; the characteristics of the curve cannot be interpreted directly as applying to the independent variable ξ (diameter in mm.). If the results are to be interpreted in terms of diameters, it is necessary to transform ϕ to ξ by means of equation 2. Usually it is not necessary to make the transformation, inasmuch as the phi values are themselves directly interpretable, and readily visualized.

GEOMETRICAL PROPERTIES OF THE NORMAL PHI CURVE

Because of the nature of the normal phi curve, its geometrical properties may be taken directly from standard statistics texts (Camp, 1931) which describe the conventional normal law. Among the more important properties of the curve are the following:

1. The area under the curve is unity. (This may be considered as 100 per cent in sedimentary data.)
2. The curve is bell-shaped and symmetrical about its mean value, M_ϕ.
3. The curve is completely described by its two parameters, M_ϕ and σ_ϕ.
4. The skewness of the curve is zero. Mathematically, the third moment about the mean, m_3, expressed as $\alpha_3 = m_3/\sigma_\phi^3$, is zero. Geometrically this restates the symmetry of the curve, inasmuch as skewness is a measure of asymmetry. A common formula for skewness is $Sk_\phi = \alpha_3/2$.
5. The kurtosis of the curve is zero. Mathematically, the fourth moment about the mean, m_4, expressed as $\alpha_4 = m_4/\sigma_\phi^4$, is numerically equal to 3.0. Kurtosis is defined as $k_\phi = \alpha_4 - 3$, and hence is zero in the normal curve. Kurtosis is a measure of the degree of peakedness; when $\alpha_4 > 3$, the curve is leptokurtic; when $\alpha_4 < 3$, the curve is platykurtic.

The last condition raises an interesting point regarding frequency curves. The necessity of α_4 having a fixed value means that symmetrical frequency curves are not necessarily normal. The writer's experience has been that symmetrical curves are not uncommon among certain types of sediments, but curves having values of α_4 close to 3.0 are comparatively rare among the samples studied. Just what the significance of this is in sedimentary terms is not clear. So little data have been published on the logarithmic moments of sediments that generalizations are not possible.

Among the properties mentioned above certain ones are of considerable significance in sedimentary petrology. The fact that the normal curve is completely described by the phi mean and the phi standard deviation means that the sum total of environmental factors which control the size characteristics of the sediment are summarized in these two parameters. Quantitative studies of the variations of M_ϕ and σ_ϕ over an environment of essentially normal curves may yield data of value in developing theories of sediment transportation and deposition. Similar studies of environments of symmetrical curves, including an investigation of the areal variation of α_4, should throw light on the significance of the latter parameter.

TESTS FOR PHI NORMALCY

Certain of the properties of normal

curves may be used to test experimental data for normalcy. For example, if $\alpha_3 = 0$, and $\alpha_4 = 3.0$, the distribution is normal. This inspection of the higher moments is one of the simplest analytical tests. A graphic test, using probability paper,

TABLE 1.—*Mechanical composition of marine shale* (A), *and beach sand* (B)

Grade Sizes (mm.)	ϕ	Sample A	Sample B
1–1/2	0–1	—	4.9%
1/2–1/4	1–2	—	58.9
1/4–1/8	2–3	—	36.0
1/8–1/16	3–4	1.3%	0.2
1/16–1/32	4–5	2.4	—
1/32–1/64	5–6	7.3	—
1/64–1/128	6–7	24.4	—
1/128–1/256	7–8	32.0	—
1/256–1/512	8–9	15.8	—
1/512–1/1024	9–10	11.0	—
1/1024–1/2048	10–11	5.8	—
		100.0%	100.0%

indicates whether the curve is symmetrical, but does not, as far as the writer is aware, offer any simple means of evaluating α_4.

Another test for normalcy, which is more tedious than the above, is the Chi square test for goodness of fit. For that test the curve is assumed to be normal, and the theoretical frequencies associated with each class are determined from tables of the probability integral. The observed and calculated frequencies are then compared in terms of the departures of the observed data from the calculated. This is summarized as the probability of obtaining a random sample from a normal universe of worse fit than the observed sample. For sample A the probability of obtaining a worse fit is 1 of 2.5 chances, indicating that the assumption of normalcy is justified. Details of the use of the probability integral and the Chi square test are given by Camp (1931), Mills (1924), and others; Mills' discussion (pp. 527–547) is excellent for the non-mathematical reader.

Table 1 shows the mechanical composition of two sediments. Sample A is a gray marine Pennsylvanian shale from the top of the Macoupin cyclothem in central Illinois, and sample B is a beach sand from the southern shore of Lake Michigan. Sample A was analyzed by the pipette method; B was sieved. Figure 1 shows the histograms of these samples, drawn in the conventional manner. The figures are not symmetrical, and at first glance one may assume that both are slightly skewed. It has been emphasized in the past, however (Krumbein, 1934), that the raw histogram data are not always reliable for direct statistical interpretation.

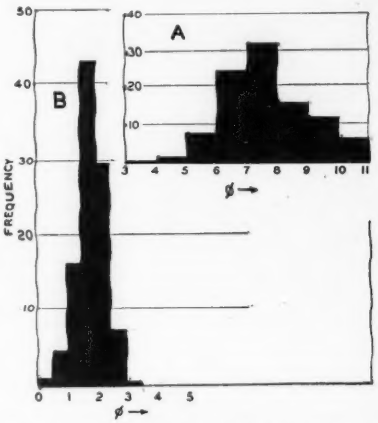

FIG. 1. Histograms of marine shale (A) and beach sand (B). Data from Table 1.

The statistical parameters of the samples, based on the first four moments,

TABLE 2.—*Parameters of two sediments*

Parameters	Sample A	Sample B
M_ϕ	7.54	1.81
σ_ϕ	1.44	0.56
α_3	+0.02	−0.02
α_4	3.10	2.47

are given in Table 2. The moments were computed by the "short method" described elsewhere (Krumbein, 1936). The

theory of the method may be found in Camp (1931).

An examination of the parameters indicates that sample A may be considered normal, but sample B is platykurtic, owing to the small value of α_4. In both cases the skewness ($\alpha_3/2$) is negligible, so that both distributions are essentially symmetrical. To illustrate the parallelism of the graphic test for symmetry, Figure 2 shows the data of the two samples plotted on arithmetic probability paper, according to the method of Hatch and Choate (1929).[1] It is interesting to note that sample B fits its theoretical straight line as closely as sample A, although the latter is more nearly normal. The departure of the points from the straight line indicates the freedom which may be used in smoothing experimental data.

Hatch and Choate (1929) describe the manner of reading the mean and the standard deviation with logarithmic probability paper. For the phi notation the practice is slightly different. The phi mean is the phi value at the 50 per cent line. This is found to be 7.55 for sample A, which is in close agreement with the computed value of Table 2. To find the standard deviation, the phi value at 50 per cent is subtracted from that at 84.1 per cent. In the graph for sample A this yields $9.00 - 7.55 = 1.45$, which is also in good agreement with the computed value. The theory involved in determining σ_ϕ graphically is merely that the range from M_ϕ to σ_ϕ includes 34.1 per cent of the distribution in a normal curve. Inasmuch as σ_ϕ is measured in phi units, the subtraction between the phi values at 84.1 and 50 per cent, or between 50 and 16.9 per cent, yields the appropriate value: $\sigma_\phi = (\phi_{84.1} - \phi_{50}) = (\phi_{50} - \phi_{16.9})$.

[1] Hatch and Choate used logarithmic probability paper for their graphs because they plotted diameters in mm. Arithmetic paper may be used for the direct plot of the phi values with the same net effect. This paper is supplied by the Codex Book Co., New York. It is their No. 3127.

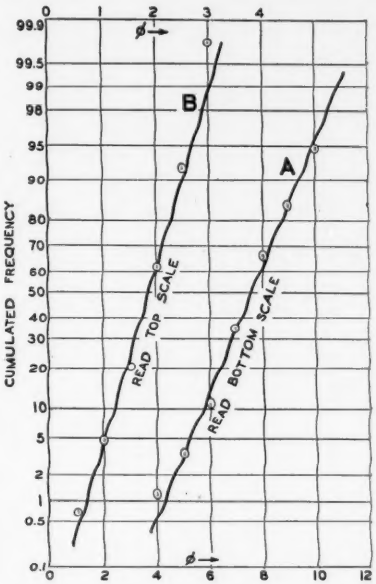

FIG. 2. Cumulative curves of marine shale (A) and beach sand (B) on probability paper.

PHYSICAL SIGNIFICANCE OF NORMAL PHI CURVES

In the final analysis statistical devices are merely numbers which summarize the characteristics of frequency distributions. Their values, however, depend upon the physical factors in the environment which produced the sediments. Among the factors which influence the observed statistical parameters of sedimentary samples are (1) the sampling process, (2) errors of splitting, disaggregation, and mechanical analysis, (3) errors of plotting and computing, and (4) various environmental factors of transportation and deposition. The first three factors are matters of technique, and the presumption is that they may be eliminated by further refinements of methods. Assume that the data are free of these influences, i.e., that the sample is representative of the deposit at the point

of sampling, that the analytical data adequately reflect the characteristics of the sample, and that no arithmetic errors have been made. The frequency distribution of the sample will then have fixed values of the first four moments which must depend upon the sum total of environmental factors at the point of deposition. These environmental factors (item 4 above) may be subdivided into:

a. the size frequency distribution of the source rock, either as primary grains in igneous rocks, or as clastic particles in an earlier sediment,

b. changes in the nature of the load during transportation to the site of deposition, due to
   1. abrasion, impact, and other wearing-down processes,
   2. deposition en route,
   3. additions to the load,
   4. combinations of the above,

c. the nature of movement of the fluid, i.e., turbulent or laminar,

d. selective depositional effects at the site of sampling due to (*c*) above,

e. coagulation of small particles during deposition,

f. authigenic changes after deposition.

These factors affect the parameters of a sample taken at a fixed point. If the sediment as a whole is considered, from source to final extent, continuous changes in the nature of the load and possibly in the energy of the transporting medium may result in progressive changes in the parameters. The mean size (i.e., the diameter-equivalent of the phi mean) will probably decrease exponentially or otherwise in the direction of travel, and the phi standard deviation ("the degree of sorting") may change or may remain fixed. The third phi moment (α_3) may behave as a periodic function of distance. That is, if the original distribution is skewed toward large sizes of particles (small values of phi), selective deposition may involve changes in the distribution such that the skewness diminishes until the curve is normal, whereupon continued transportation may develop oppositely skewed distributions. Miss Gripenberg (1934) has developed a theory of the effect of (laminar) transportation on the size characteristics of sediments. By the use of the phi notation it can be shown according to Miss Gripenberg's theory that an initial load of a normal phi curve develops increasingly positive skewed distributions during transport, due to selective deposition en route. The fourth moment (α_4) may also vary, and it is not impossible that it may describe periodic fluctuations about the value 3.0. A complete theory of sediment transportation must take into account all the factors listed above, as well as predict the changes of the parameters with distance from source.

Unfortunately, there is so little material published on the logarithmic moments of sediments that generalizations are hazardous. A theory of transportation and deposition from dynamical principles is possible, but the analysis is probably more convenient with diameter as independent variable than with phi. However, the final equations may be transformed into series which contain the logarithmic moments, to afford simple statistical methods of checking the theory. Despite the difficulties of the subject the writer would like to point out one method of approach involving the phi notation. By confining attention to a sample collected from a given point, and by further restricting attention to normal phi curves, the problem is simplified, inasmuch as only the first and second moments are involved. That is, the sum of environmental factors is summarized in M_ϕ and σ_ϕ, because the third moment (α_3) is zero, and the fourth moment (α_4) is fixed in value. Unquestionably certain definite limitations must exist in the environmental factors at the site of deposition in order that a normal phi curve may be developed.

Referring back to the environmental factors listed earlier, it may be seen that the normal phi curve at the point of deposition must involve the entire pre-

vious history of the transported load. One possible situation which may result in a normal distribution involves the periodic change in the third moment, already discussed. If at the site of deposition the material dropped from transportation has a zero third moment, the curve will be symmetrical. If combined with this is that combination of factors which fixes α_4 at 3.0, the sediment will be normal. This development suggests that probabilities may play a part, and an inkling of their rôle may be had by considering the geometrical properties of the normal phi curve.

It can be shown from equation 3, which defines the normal phi curve, that the sum of the positive and negative phi-deviations about M_ϕ must be zero. That is, there is an equal probability that the phi value associated with any particle will be either larger or smaller than M_ϕ. Indeed, this condition may be used as a starting point in developing the normal phi law as a probability function. Inasmuch as the phi mean, the phi median, and the phi mode all coincide in a normal phi curve, it is also true that the same probabilities hold with respect to the phi mode. If the phi distribution is transformed to its diameter-equivalent, however, the probabilities associated with the diameter values change significantly. That is, the mode of the diameter distribution is shifted toward smaller sizes, whereas the median and geometric mean are essentially unaffected.[2] This requires that the distribution of grain diameters about the mode be unsymmetrical, with a wider spread toward the larger sizes. Hence there is a greater probability that a given grain will be larger than the mode than that it will be smaller than the mode. Moreover the probabilities must be such that a normal phi curve results when the diameter distribution is plotted on a logarithmic size scale.

In an attempt to find physical conditions which may satisfy these requirements, the writer examined a number of pitot tube records of wind velocities at the University of Chicago weather observatory. Figure 3 is a tracing of part of such a record. The vertical lines represent velocity fluctuations, which occurred about once a minute on the average. The pulsations are asymmetrical, with the maximum velocities rising above the solid belt more conspicuously than the minimum values drop below it. Now the radius of a transported (or deposited) particle is a function of some power of the velocity of the transporting medium. The lowest velocities will control the smallest particles deposited, and the highest velocities will control the largest particles carried. The bulk of the grains will presumably be controlled by the average velocities in the main belt of the graph. It appears likely from the graph that deviations of grain size will be greater above the average belt than below. In particular cases the ratio of the deviations may approach a value which satisfies the conditions of asymmetry demanded by the foregoing analysis. Under these conditions the phi distribution will approach normalcy in the degree to

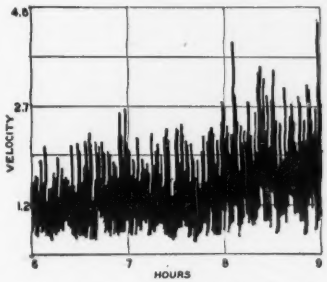

FIG. 3. Portion of pitot tube record of wind velocity.

[2] The mathematical relations between the normal phi curve and it corresponding diameter curve are complex. Preliminary analysis suggests that in the transformation from ϕ to ξ the mode shifts a distance of approximately $+0.7\sigma_\phi$ in the case where $\sigma_\phi = 1$. That is, the modal diameter is about 3/4 of a Wentworth grade smaller than the median or geometric mean diameter in this case.

which the phi deviations are equally distributed about the phi mean.

This simple situation demands the simultaneous satisfaction of many other conditions, some of which were listed earlier. The example is given not as a theory of normal phi curves, but merely to indicate that physical conditions may be found which apparently correlate with the requirements of the geometry of the normal phi curve. It is probably an error to assume that only turbulent conditions develop such curves. The marine shale mentioned earlier (sample A) is normal, but it is doubtful whether turbulence was associated with its deposition. In all likelihood the development of normal phi curves is possible under a variety of physical conditions, but each set of conditions must have certain limitations. In a complete dynamical theory of sedimentation it may be found that normal phi curves represent limits toward which conditions tend under certain circumstances.

SUMMARY

The principal purpose of the present paper is to indicate that logarithmic moments of mechanical analysis data may be useful not only in the description and comparison of data, but in restricted cases may suggest lines of further study in the genetic evaluation of sediments. As additional data on the parameters of sediments are collected, and as these parameters are studied in terms of their areal variation, it may be expected that significant generalizations will be possible. In the opinion of the writer the continued accumulation of quantitative data about sediments is a pressing need; paralleling such studies may be the development of theories of transportation and deposition which afford generalizations of the observations, and may predict important new data. Such researches will permit a more detailed analysis of present environments, and will pave the way for more thorough understanding of ancient sedimentary conditions, with their practical importance in historical geology and in the location of economically valuable deposits associated with sedimentary environments.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 8, NO. 3, PP. 91–99, TEXT-FIGS. 1–4, PLATE 1, DECEMBER, 1938

OCCURRENCE AND ORIGIN OF CERTAIN LIMONITE CONCRETIONS

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ABSTRACT

Limonite concretions which occur in a Pleistocene conglomerate near Iowa City, Iowa, are divided into two groups according to origin. The concretions of the first group, for which the term parogenetic is introduced, were incorporated in the conglomerate as clastic units, having been formed in a pre-existing rock. The parogenetic concretions are of two types, those with a limonite shell which is filled with argillaceous calcium carbonate and those whose shell is nearly or entirely empty. The second group consists of concretions which originated when gravel was cemented to form the conglomerate, and hence are syngenetic. The latter concretions are irregular masses of glacial till around which ferric hydroxide has cemented the materials of the conglomerate into a shell or crust.

INTRODUCTION

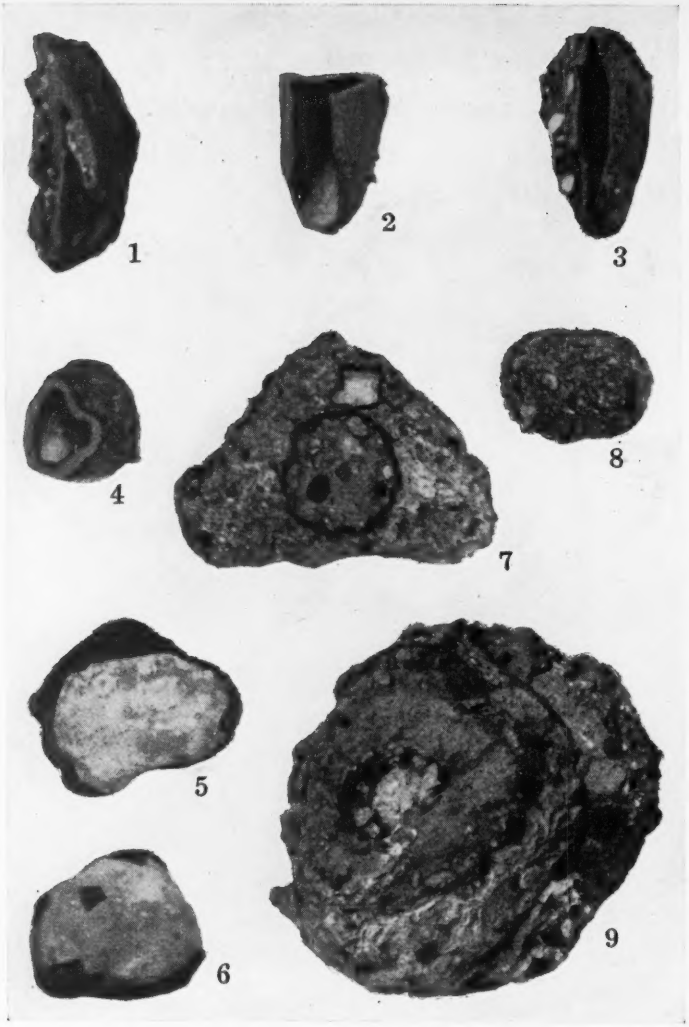
At the east end of a limestone quarry 2 miles northwest of Iowa City, Iowa, there is exposed a section of early Pleistocene glacio-fluvial materials overlying bedrock. A layer of cross-bedded conglomerate 6 feet in thickness lies between thicker beds of sand. The materials composing the conglomerate vary in size from coarse sand to cobbles, with a preponderance of pebble sizes. The composition of the constituent pieces is also variable. Quartz is abundant, and there are fragments of many types of rocks, including dense cryptocrystalline Cedar Valley limestone, the bedrock formation. Abundance of iron oxide is shown by the brownish-red color of the exposure. Chemical tests show the oxide to be one of the compounds embraced by the term limonite. Besides acting as the cementing agent of the conglomerate, the limonite occurs as dark red films on rock fragments, and in the form of concretions.

The concretions are characterized by the possession of a shell or crust of limonite surrounding a less ferruginous mass which may or may not fill the space within the shell. They are here divided into two groups on the basis of origin. Many of the concretions were obviously formed in a different rock from their present host. They were then removed from that rock, transported, and deposited in a gravel which later became a conglomerate. For these concretions the term parogenetic is proposed, from the Greek *παρος*, before or formerly. The meaning of the term is "formed before the enclosing rock." It is in strict correspondence with the terms syngenetic (formed at the same time) and epigenetic (formed later or upon). The parogenetic concretions are of two types, referred to for convenience as solid and hollow. The second group of concretions are syngenetic, i.e., they were formed at the same time as the conglomerate.

SOLID PAROGENETIC CONCRETIONS

Description.—These concretions vary in outside diameter from about ½ inch to 6 or 7 inches. As a rule they are roughly equidimensional. The shell is generally thin in comparison to the size (text-fig. 1; pl. 1, figs. 5, 6). Thus in a concretion with a maximum diameter of 3 inches, the shell may be but 1/10 inch thick. It wraps closely around the material within, and may be either dark red, hard, and strong, or yellow-brown, soft, and friable. The texture of the crustal material is not different from that of the inner part; the shell is a zone of the original material which is strongly impregnated with limonite. The outside surfaces of these crusts are smooth.

The central mass, which is uniformly



EXPLANATION OF PLATE 1

FIGS. 1–4.—Hollow parogenetic concretions. Material from the conglomerate adheres to the outside of the shells, but the latter are clear-cut and are not penetrated by the attached pieces. $\times\frac{1}{2}$.

FIGS. 5 and 6.—Solid parogenetic concretions. Argillaceous calcium carbonate surrounded by thin shells of limonite. $\times\frac{1}{2}$.

FIG. 7.—Piece of the conglomerate showing part of a syngenetic concretion with the central mass removed. Clastic materials are cemented into the shell. At top, a small solid parogenetic concretion. $\times\frac{2}{3}$.

FIG. 8.—Small unbroken syngenetic concretion. $\times\frac{1}{2}$.

FIG. 9.—Syngenetic concretion broken open to show concentric zoning. $\times\frac{1}{3}$.

fine-grained, invariably has a high content of calcium carbonate. Samples of the central masses of 6 specimens were digested in dilute HCl in order to determine their percentages of soluble material. It was found that from 63 to 94 per cent of the mass was soluble, the average for the 6 specimens being 81 per cent. The insoluble residue, represented in the average by 19 per cent, consisted either of uniform silt composed of angular quartz grains, or of buff clay, powdery when dry and unctuous when damp.

Two of the specimens examined were sufficiently indurated that sharp hammer blows were necessary to break them open. Others were soft and friable and left a yellow powder on the hands. The larger concretions may contain several inner shells of limonite, which are generally thinner and less smooth in outline than the outside one. One specimen which the writer collected had 8 thin zones of limonite in the mass enclosed by the outer layer.

Origin.—It is nearly always assumed that concretions have been formed in their present positions in the rock in which they are found. This is undoubtedly true for the great majority of concretions. That such is not the history of the concretions now under discussion is strongly indicated by the following evidence.

The concretions are cemented into the conglomerate exactly as a pebble or cobble of the same size would be (text-fig. 1). That is, adjacent sand grains and pebbles are in contact with the outside of the limonite shell, but they do not penetrate that shell or come in contact with the central calcareous mass. The conclusion is plain that the shell was present in a solid form before the concretion was incorporated into the conglomerate. The concretions were deposited as clastic units.

If it be maintained that the concretions were contemporaneous in origin with the gravel which preceded the conglomerate, it is difficult to explain how a mass of fine material, in some cases 94 per cent calcium carbonate and of doubtful resistance to abrasion, could become emplaced in a gravel and resist chemical attack long enough to acquire a limonite coating.

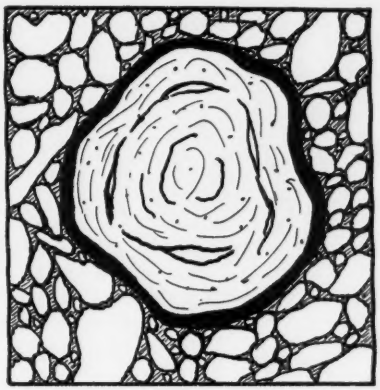


FIG. 1. Diagrammatic cross-section of a part of the conglomerate to show the emplacement of a solid parogenetic concretion. Solid black = limonite; shaded areas = limonite-cemented sand forming the matrix in which the larger pieces are embedded.

If we follow the evidence set forth above, our account of the concretions' origin does not have to be entirely conjectural. That concretions very similar to these form in glacial clays has been shown by Kindle (1923). Their practical identity with the concretions here described is indicated by the following remarks:

> Sharp contrasts between the composition of the outer shell and the interior portion is one of the characteristics worthy of note. . . . The elongate forms found on the south bank of the Hamilton River are composed chiefly of argillaceous calcium carbonate. A thin shell of limonite surrounds this interior portion of the concretion. Many of these concretions consist of a hard, well-indurated material encased in a thin shell, sometimes a sixteenth of an inch or more in thickness, consisting of a

very soft material easily indented by a knife point or the thumb nail.

The concretions thus described occur in clays which comprise the lowest part of the Pleistocene section in eastern Labrador. They were formed in those clays. Here then is a possible mode of occurrence for the solid parogenetic concretions found in the Iowa conglomerate.

The history of these concretions may be reconstructed as follows. Somewhere to the north of the conglomerate deposit, calcium carbonate concretions were formed in beds of clay and silt. As no nuclei were found in the specimens studied, the first particles of the carbonate precipitated by a change in physical conditions may have acted as a center of growth; or possibly, as Kindle (1923, p. 617) suggests, the nucleus may have been provided by inorganic salts accumulated in the tissues of a shell-less mollusc which left no trace in the sediments. The concretions were formed near the ground water surface in the clay or silt deposit, where carbon dioxide could escape from the calcium bicarbonate solution. The presence of considerable clay and silt in the concretions suggests that the attraction between molecules of the carbonate was too weak to exclude surrounding material entirely.

The waters which permeated the clays and silts and their concretions carried considerable iron in the form of the ferrous carbonate. When the deposits began to dry out, the concretions which were affected by drying began to lose moisture first at their outer surfaces. The carbonate became oxidized and was precipitated as ferric hydroxide. Molecular attraction of the hydroxide probably removed the iron from both the outer part of the concretion and the adjacent clay or silt and concentrated it in a zone. Thus a shell was gradually built up. The concentric limonite laminae within the mass have been explained by Dana (1895) and discussed by Todd (1903). The zoning is supposed to be analogous to the drying of a drop of an emulsion, such as milk, on a flat surface, where successive rings are deposited as the moisture within the spot retreats by stages toward the center. In the case of a sphere instead of a ring, Todd suggests that we may suppose

> an alternating action between carbonic acid and oxygen in the water as the water gradually withdraws by drying.

It has been mentioned that some of these concretions are hard and others soft. The former are but moderately porous, while the latter have a high porosity. If the concretions were formed as outlined above, we should expect a different distribution of limonite in the porous and less porous concretions. Such a difference exists. The porous concretions have a thin shell of limonite which readily chips off and they contain, as a rule, many thin laminae of iron oxide. The more impervious forms, on the other hand, have a relatively strong, thick shell and few if any interior zones. These facts show the tendency of the less porous concretions to keep the iron hydroxide precipitate concentrated on the outside of the mass in a thick crust. The porous concretions allowed more rapid drying out, causing the formation of a thinner outside crust and several interior ones.

After the concretions had taken on essentially their present form, erosion attacked the deposits in which they lay and liberated them. Their insoluble crust of limonite provided protection from chemical and mechanical attack. They were picked up in the course of time by a glacier-fed stream, and transported probably for only a relatively short distance. When the stream reached the present site of the conglomerate, it dropped its coarsest load and the concretions became incorporated, along with other clastic materials, in a glacial gravel. Subsequent consolidation has preserved them in the conglomerate which we see today.

HOLLOW PAROGENETIC CONCRETIONS

Description.—The concretions which are partly or entirely hollow are extremely

abundant, far exceeding the other types in number of individuals. (See text-fig. 2; pl. 1, figs. 1–4.) Their outside diameters range from a small fraction of an inch to 3 or 4 inches. Some layers of the conglomerate are largely composed of small concretions of this type mixed with pebbles and coarse sand, the mixture loosely cemented by limonite. The shell is typically dark red, hard, and relatively thick. One specimen with an outside diameter of 1.3 inches has a shell which is 0.3 inch thick. The shells of many specimens show concentric laminations. Generally pebbles and sand grains adhere to the outside of the concretion, but they do not penetrate into or through the shell. The inner wall of the shell, which is sharply separated from the central mass, is usually covered with a film of clay. Reniform or mammillary growths on the inside of the shell are common; they are made up of limonite like that of the shell. In flattened forms, protuberant interior growths on either side may coalesce and form a brace across the internal cavity.

An effort was made to remove all the iron oxide from fragments of the shells of three specimens, by digestion in a strong solution of stannous chloride. It was found that on the average more than 77 per cent of these crusts consisted of limonite. The remainder after the $SnCl_2$ treatment was composed of clay and silt with a few fine grains of quartz sand. In the residue from two of the specimens, very small flakes of muscovite were detected.

The central mass in concretions of this type is variable in texture and composition. A number of examinations under the binocular microscope has shown that any of the following may occur: silt, friable when dry, with a few small quartz grains; silt, dark gray, with many subround to subangular quartz grains; clay, buff, non-calcareous except for a few very minute crystalline aggregates of calcium carbonate; clay, slightly calcareous, with starchy fracture; fine quartz grains held together by a film of clay. A common form taken by sand grains when bound by a clay film is a rough cone, based on the inner wall of the shell and extending toward the center. In one specimen the filling consisted of quartz sand masked by a small amount of yellow clay, surrounding a compact mass of clay with embedded quartz grains. This compact "kernel," on being broken open, revealed three concentric zones of limonite.

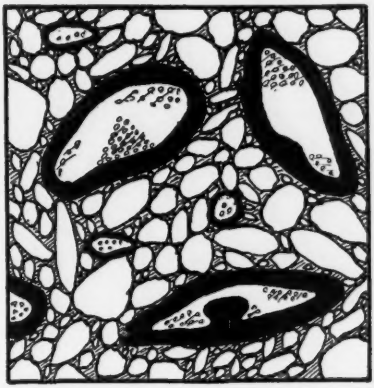


FIG. 2. Diagrammatic cross-section of a part of the conglomerate to show the emplacement of hollow parogenetic concretions. Solid black = limonite; shaded areas = limonite-cemented sand forming the matrix in which the larger pieces are embedded.

Features which are common to all the specimens examined are, first, a very low content of calcium carbonate; second, the failure of the central mass to fill the void within the shell; third, the unsorted character of the concretionary material. What little calcium carbonate is found is generally not disseminated through the central mass, but occurs as aggregates in the mass or as tiny crystals on the inner wall of the shell. The strong carbonate reaction of the solid parogenetic concretions is entirely lacking. Some of the concretions approach solidity, with a mass which loosely takes up the space within the shell; others are empty. In most specimens, 20 to 50 per cent of the cavity is

occupied. Not only may the central mass consist of mixed sand, silt, and clay, but it was found that the non-ferruginous residue from the shell is also heterogeneous in grain size.

Origin.—As in the case of the solid parogenetic concretions, the evidence points strongly to the conclusion that the hollow concretions were in their present form before incorporation into the conglomerate. Their relation to other pieces in the rock (text-fig. 2) shows plainly that they are cemented into the rock in exactly the same manner as a piece of quartz or igneous rock of corresponding size and shape. Hence the conclusion is obvious that they were formed in a pre-existing rock.

Several possible modes of origin suggest themselves:

1. The concretions may have formed from the weathering of pebbles and cobbles of basic igneous rock which were high in iron content. The presence of clay, quartz, and mica in the concretions may be cited as evidence, and also the fact that in the conglomerate there are a few pieces of diabase which have a thin crust of iron hydroxide surrounding them. However, the objections are numerous and weighty. The abundance of the concretions suggests their formation in this or a preceding conglomerate, which is unlikely for reasons stated above. There is little or no feldspar present, and the mica, instead of being the dark variety found in basic rocks, is muscovite and occurs in tiny flakes throughout the conglomerate. Occasional fragments of igneous rock occur in the central masses of these concretions, along with the clay and quartz. Finally, it is questioned whether the required amount of iron could be produced by the weathering of even very basic igneous rocks.

2. The concretions may have formed similarly to the solid parogenetic forms, i.e. the limonite may have accumulated around a mass of calcium carbonate. Later the carbonate may have been leached out and carried away, leaving behind an insoluble residue which only partly filled the shell. However, it is difficult to visualize the removal of calcium carbonate in solution through a solid wall of compact limonite $\frac{1}{4}$ inch thick. Some of the true solid concretions have far thinner and less dense walls but retain their soluble central mass intact.

3. The concretions may have been formed as the result of the oxidation of pre-existing concretions of marcasite or pyrite. Merrill (1894) has demonstrated such a history for irregular hollow concretions of ferruginous sand in the Potomac beds of Cretaceous age near Washington, D.C. The iron oxide segregated in zones around nodules of pyrite, cementing the sand grains and forming a dense crust. In cases where the pyrite was not pure, but enclosed sand grains, the grains remained behind as partial filling. Merrill explains the presence of the pyrite by the nearby occurrence of lignitized logs, gases from the decomposition of which may have reduced iron sulfate to the disulfide. Objections to this theory of origin when applied to the concretions under consideration include the total absence of iron disulfide from the concretions at present, and the question as to whether either lignite or sulfate waters existed in the parent deposit in the proper conjunction for the formation of the many concretions of this type. The absence of pyrite may be due to the severe ground water action which has affected the conglomerate during the long time since its deposition. However, the rarity of fossilized wood and the preponderance of carbonate waters over sulfate waters in later glacial deposits suggest that pyrite was not the forerunner of the hollow parogenetic concretions.

4. The concretions may have formed from claystones in which the predominant concretionary mineral was siderite. The abundance of sideritic concretions in clays is well known, and there is no reason why they should not be commonly formed in less well-sorted deposits such as till. Todd (1903) explains the forma-

tion of hollow iron oxide concretions on this basis. His views are excellently summarized by Grabau (1913):

> Todd holds that normal accretions or intercretions of ferrous carbonate, on coming in contact with waters charged with carbon dioxide and oxygen, will begin to dissolve, and a shell of ferric hydroxide will form on the surface by precipitation. The iron carbonate of the portion of the concretion within this shell will similarly be dissolved. . . . The impurities of sand and clay in the original concretion remain behind in a loose condition. . . . When the process is completed, a loose mass of sand and clay may be left, or if the original concretion was pure, the shell may be hollow.

Such an explanation seems applicable to the concretions in question. It may be assumed that the waters which penetrated the beds in which these concretions formed were carbonate waters which would yield siderite rather than pyrite on deposition. The slight carbonate content of the central masses of some of the concretions may be better explained in this manner.

The history of the hollow parogenetic concretions may be summarized as follows: (1) the formation in glacial till of siderite concretions, most of which were not pure siderite but included some of the surrounding material which was not excluded when the mineral collected; (2) solution of the iron carbonate and precipitation of ferric hydroxide as a crust around the outside; (3) disintegration of the deposit by erosion and the removal of the concretions in glacio-fluvial waters; (4) deposition of the concretions in a gravel which later became the present conglomerate by cementation.

SYNGENETIC CONCRETIONS

Description.—The syngenetic concretions, which occur at scattered points throughout the conglomerate, differ markedly from those already discussed. On the average they are larger, varying from an inch or more up to 8 or 9 inches in outside diameter. They are invariably characterized by an extremely rough, pebble-studded shell, which consists of a spherical or ellipsoidal zone of limonite with agglutinated smaller constituents of the conglomerate. (See text-fig. 3; pl. 1, figs. 7–9.) In a specimen 8 inches across, a zone of limonite ½ inch thick may extend irregularly around the outside, surrounding or embedding whatever sand grains, pebbles, or smaller concretions lie in its path. A pebble an inch or so in diameter may extend completely through such a shell, one end in contact with the conglomerate and the other protruding into the central mass of the concretion.

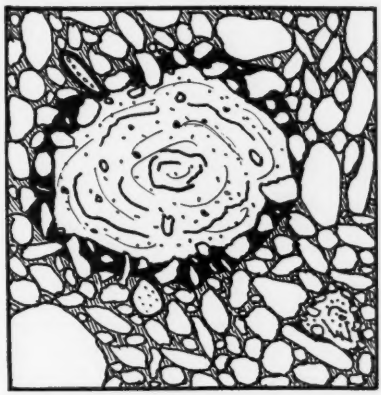


FIG. 3. Diagrammatic cross-section of a part of the conglomerate to show the emplacement of syngenetic concretions. Solid black = limonite; shaded areas = limonite-cemented sand forming the matrix in which the larger pieces are embedded.

In the spaces between cemented pebbles, the limonite crust may be roughly laminated concentrically. The strength varies in different specimens. Some have hard, firmly cemented shells (which are not always the thickest ones), whereas others have crusts so weak that they exercise little or no restraint on the enclosed material and the whole concretion collapses readily.

The central mass, which is completely

unsorted, consists of glacial till. One of the specimens studied contained abundant clay in which were embedded grains and pebbles of limestone, sandstone, quartz, granite, basalt, schist, and chert.

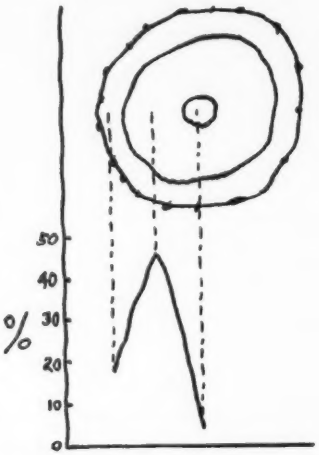


FIG. 4. Per cent of ferric hydroxide in three till zones of a syngenetic concretion.

The clay was calcareous and contained many white calcium carbonate concretions of the well-known "loess-kindchen" type.

Origin.—The concretions under discussion were formed in their present positions in the conglomerate, as is shown conclusively by the occurrence of clastic elements cemented solidly into the shell. Their formation probably took place as an incident to the consolidation of the pre-existing gravel into the present conglomerate. The cementing agent, limonite, which permeated and bound together the entire mass, became concentrated at certain places. The resulting concretions thus were formed after the deposition of the gravel, but contemporaneously with the formation of the conglomerate. Hence they are to be classed as syngenetic.

Let us assume that the current which carried materials into the gravel sharply undercut a bank of till. Fresh, wet, argillaceous blocks fell off and were seized upon by the current. Some probably broke up completely, but many withstood the buffeting and were rolled along the bottom. As the current was heavily loaded with clastics of all sorts, many of which were on the bottom of the channel, the till masses acquired an outer layer of adhering sand grains, pebbles, and parogenetic concretions. That clay balls gather material by adhesion is well known. By the time the masses of till had reached their resting-places in the gravel, they were heavily studded with fragmental materials. Formed and emplaced entirely by mechanical means, these till masses are not classed as concretions till a later stage in their history.

At some time after its deposition the gravel was subjected to alternate saturation and desiccation by ground water which was rich in iron. Inasmuch as carbonate waters are more common than sulfate waters in Pleistocene deposits in this part of Iowa today, it is permissible to assume that the iron was in the form of the soluble bicarbonate. The source of this iron is unknown. There were abundant parogenetic concretions in the gravel, but they were sheathed with insoluble limonite and it is believed that the iron of their shells did not go into solution. Perhaps the ultimate source of the iron was the same as the one which provided the limonite for the parogenetic concretions in the earlier clays, silts, and till beds. When periodic drying out of the gravel took place, the carbonate of iron was oxidized to the ferric hydroxide and precipitated throughout the deposit. It formed films between grains and pebbles, cementing the gravel into a conglomerate; and it concentrated especially in and around the clayey masses of till.

The specimen shown in pl. 1, fig. 9, illustrates this type. This concretion, which is some 7 inches in outside diameter, consists of three shells of limonite alternating with three thicker zones of

till. The outside surface is extremely rough, due to adhering pebbles set firmly in limonite which is from ¼ to ½ inch thick. The material within this crust is yellow glacial till. About one inch from the inner limit of the outer crust is a second well-defined subspherical shell of limonite, about 1/8 inch thick. It encloses a zone of till which carries thin irregular concentric limonite laminae. A third limonite zone occurs within this mass. It is 1/10 inch thick and 1 inch in outside diameter. Within this crust lies a loose kernel of mixed sand, silt, and clay, light gray in color.

Tests for content of iron hydroxide were made for all three till zones. The results are shown graphically in text-fig. 4. The sharp rise in limonite content shown by the intermediate zone is due to the greater thickness of that zone and its thin, discontinuous veinlets of limonite. The outside till zone, relatively thin and located between two limonite crusts, lost more of its iron; the innermost core lost nearly all its iron to the central crust. But the thickness of the intermediate zone shows that desiccation took place rapidly, allowing much hydroxide to be precipitated but spreading it over a wider area.

When, after saturation, the conglomerate started to dry out, the last parts to become dry were the clayey till masses. Once thoroughly wet, these masses would act as centers of moisture in the drying conglomerate. The ferric hydroxide, precipitated as a result of desiccation of the normal porous conglomerate, formed films and acted as a cement. However, the hydroxide in the vicinity of the till masses precipitated on the outside of those masses as the water was drawn to them by capillarity. Perhaps only a thin film was laid down at one time; continued conditions of alternating saturation and drying would thicken the shell. As the moisture retreated farther into the till masses, additional zones were precipitated when pauses in the retreat took place. When retreat was rapid, several thin limonite zones formed. Thus may be outlined the formation of the syngenetic concretions.

CONCLUSIONS

The resemblance between the suggested mode of origin of the syngenetic concretions and that of the solid parogenetic concretions is apparent. In the former case, masses of till acted as centers around which limonite collected in a conglomerate; in the latter, bodies of calcium carbonate accumulated limonite in beds of silt or clay. It seems a logical inference that any foreign masses in an appreciably porous host-rock may serve as centers around which, under suitable chemical conditions, limonite concretions may be built up.

That concretions thus formed, or indeed those formed in other ways, may originate in one rock, be removed from it and deposited in another rock, is demonstrated by the foregoing account. Hence, although no doubt this set of events has occurred but seldom in the geologic past, it may be well to inquire, on studying a new occurrence of concretions, whether some or all of them possibly antedate in formation their present host.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 8, NO. 3, PP. 100–104, FIG. 1, DECEMBER, 1938

CORRELATION BY MEANS OF BENTONITES

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ABSTRACT

Samples were taken in the Cretaceous shale of eastern Colorado from bentonite seams of suggested stratigraphic relationship. Mechanical analyses of these samples were made to determine the value of such analyses in the correlation of the individual seams. The results indicate that individual seams may be recognized by characteristic percentages of silt, clay and colloid.

INTRODUCTION

Bentonite is defined as "a rock composed essentially of a crystalline clay-like mineral formed by devitrification and the accompanying chemical alteration of a glassy igneous material, usually tuff or volcanic ash." (1)

Pinkley and Roth (1928) use the term bentonite in quotations for altered volcanic ash deposited in western Kansas. Judging from their report the occurrence and heavy mineral content of these Kansas bentonites are the same as the bentonites treated here. The Kansas material contains no feldspar whereas it is frequently abundant in the Colorado bentonites under discussion.

The term bentonite is used in this paper to refer to material derived from alteration of volcanic ash and the bentonite described occurs in thin seams from a fraction of an inch to a few inches in thickness in the Cretaceous shale of eastern Colorado. Sixteen samples, taken from just south of Colorado Springs east to north of Kit Carson, were analyzed in this study. These samples were collected by C. S. Lavington and C. H. Rankin from the Tepee Butte zone of the Pierre formation. The analysis of the heavy minerals was made by W. O. Thompson.

These bentonites are colored in various shades of cream, yellow, brown and grey which sharply delimits them from the black shale with which they are interstratified. Almost invariably they have a soapy feel. They are usually softer than commercial bentonite and have a fracture which varies from platy to conchoidal. This material when placed in water has the same characteristic property of slumping as that possessed by commercial bentonite. The mineral assemblage also is distinctive. Heavy minerals such as magnetite, zircon and apatite occur in euhedral grains with no evidence of abrasion and the feldspar is fresh and unaltered. A cherty zone, which is the result of the devitrification of volcanic ash, is present beneath the bentonitic seam in many places.

In studying ordinary sediments the changing composition due to different conditions of deposition encountered makes correlation difficult. Bentonites, on the other hand, were derived from volcanic ash which was carried by the wind and deposited over large areas. When this material settled in quiet water and had not been reworked or transported and redeposited, it remains relatively uniform in composition over considerable areas. The seams found in the Pierre shale were deposited on the quiet surface of a large interior sea during Cretaceous time, and settled to the bottom with the minimum of contamination by foreign material. Each thin seam represents a very short interval in geologic time and, therefore, when correlated, should form the most exact marker conceivable. The size-distribution of particles in bentonites is of value in correlation only in areas of uniform deposition. The

single metabentonite bed found in the Decorah formation of Iowa, Wisconsin and Missouri emphasizes this fact (Allen, 1932). It varies in different localities in the percentage of silt, clay and colloid present. The bentonites of the Pierre shale are particularly adapted to correlation because of their deposition under uniform conditions over extensive areas. In addition, they are particularly needed in this area because there is no dependable horizon marker in this great thickness of shale.

In selecting the samples for study three criteria were used. Some of these are mentioned by Ross (1925). (1) The field occurrence. (2) The characteristic slumping when placed in water. (3) The presence of unaltered euhedral mineral grains.

The problem was to develop a method for the mechanical analysis of bentonite and to determine the value of this analysis in the correlation of individual bentonite seams.

Ross (1925) mentions the danger of attempting the correlation of material which is not derived from volcanic ash or of volcanic ash which has been mixed with a great deal of foreign material. Some samples brought in from the field emphasize this danger. They occur in yellowish seams and can easily be mistaken for bentonitic material. In the laboratory the difference readily becomes apparent. The clay material merely disintegrates when placed in water. There is no slumping action characteristic of bentonite. In addition, the fresh, unabraded appearance of the mineral grains is absent in the clay.

This correlation by means of mechanical analysis depends on two premises. (1) The same seam will show the same composition over large areas. (2) Different seams will show different compositions.

METHOD OF ANALYSIS

The pipette method of mechanical analysis was selected as that most applicable to bentonites. The key to accurate mechanical analysis of this material is good dispersion. The colloidal coatings on sand and silt grains must be removed, and the aggregates broken up into individual particles and maintained in this condition throughout analysis.

Both agitation and the use of a dispersing agent is necessary for this dispersion. The flocculation of colloidal particles depends to a large degree on the pH value of the solution and will occur if the solution is either too acid or too basic. Sodium oxalate was used as the dispersing agent. In most bentonites complete dispersion was obtained by adding 5 to 10 cc of .5N sodium oxalate solution to a 5 g. sample. The agitation was accomplished by a mechanical shaker which turned the tubes end over end 100 times per hour. Agitation was continued for different durations, up to twenty-seven days. After that length of time the sample contained the same percentage of different sized particles which proves that this method of agitation does not cause a diminution of particle size. In all cases complete dispersion was obtained in twenty-four hours, and in a few cases six or seven hours resulted in complete dispersion.

The formation of a gelatinous suspension which quickly settles, leaving a clear supernatant liquid above with a fluffy accumulation at the bottom of the chamber indicates insufficient dispersion. In a completely dispersed sample the colloid particles will cloud the solution for days, and the larger particles will settle to the bottom of the container. Some of the samples contained so much gypsum that dispersion could not be obtained.

The settling velocities for division into "silt," "clay," and "colloid" fractions used in this analysis are those adopted by the Bureau of Chemistry and Soils.

In analyzing bentonites by the pipette method a five gram sample was taken. This was placed in a dispersing tube with the dispersing agent (5 cc sodium oxalate) and sufficient water to bring the volume to 50 cc, and then shaken by

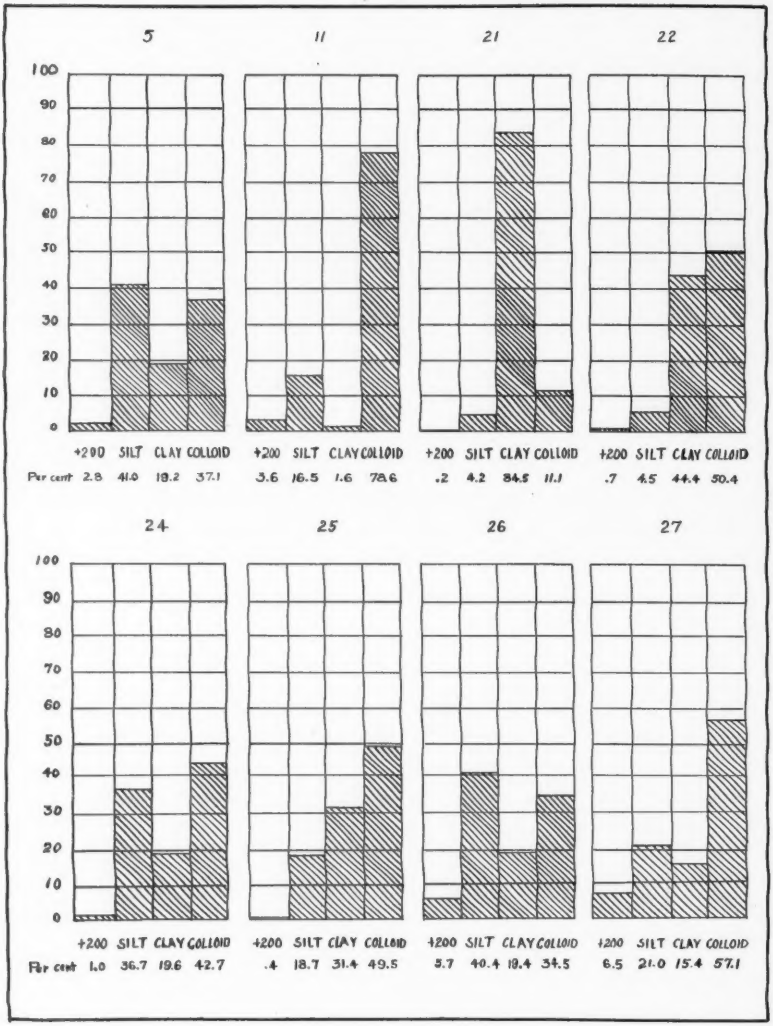

FIG. 1

hand till the swelling ceased, after which it was placed in the agitating machine for complete disintegration and peptizing. Dispersing tubes were made of heavy glass tubing with an inside diameter of 18 mm cut in 30 cm lengths. When

corked they have a capacity of approximately 75 cc.

After agitation the contents of the dispersing tube was poured through a 200 mesh sieve into a 500 cc graduated glass sedimentation chamber. All material remaining in the dispersing tube and on the corks was washed into the sieve by the stream from a wash bottle. The material retained on the screen was also washed to remove any coating on the larger grains. Since there is very little plus 200 mesh material in bentonites only the one sized mesh was used in the separation by sieves. The usual pipette method was then followed.

Duplicate and triplicate tests of the sample were always made and check very closely, indicating that the material is uniform in composition.

RESULTS

Samples nos. 5 and 24 are known to be from the same bentonite layer because of their field occurrence. At the point where sample no. 5 was taken the seam is 7 3/4 inches thick; at the point where no. 24 was taken it is 7 inches thick. These samples were taken within one-half mile of each other and are the only samples used which are positively know to be from the same bed. The physical appearance of the two is similar except that no. 5 is more stained with limonite. The mineral assemblage is identical: plagioclase feldspar, abundant; biotite, moderate; chert, fairly common; basaltic hornblende, rare. Three analyses of each sample were made and the average is given in fig. 1. These analyses do not show identical proportions of silt, clay and colloid for nos. 5 and 24 but are sufficiently so to give patterns typical of these two samples and their correlatives.

Sample no. 26, taken 16 miles west of samples nos. 5 and 24 from an 11 inch bed, was reported from the field as "may be the same as nos. 5 and 24." It is entirely different from them in appearance, containing megascopic euhedral grains of biotite and breaking in large platy chunks. The mineral assemblage is sufficiently similar to indicate a probable correlation. Biotite, abundant; plagioclase feldspar, very abundant; chert, common; zircon, very common; basaltic hornblende, rare. The mechanical analysis of this sample is the same as nos. 5 and 24 as shown in fig. 1.

Sample no. 25, taken relatively close to nos. 5 and 24 from a 7 inch seam, reported from the field as "may be the same as nos. 5 and 24." The mineral assemblage shows similarity to nos. 5, 24 and 26: biotite, abundant; plagioclase feldspar, abundant; zircon and magnetite, common; aphanitic rock matrix, fairly common. Mechanical analysis, however, shows the percentage of silt, clay and colloid in this sample to be very different from nos. 5, 24 and 26.

Sample no. 11 was taken 24 miles northwest of no. 21. Both samples came from 4-inch yellow seams with a field report stating, "may be the same." The mineral assemblage is entirely different: zircon characterizing no. 21 and basaltic hornblende no. 11. The results of mechanical analyses are as different as could be imagained in a deposit of this kind.

The analyses of nos. 22 and 27 are given in fig. 1 to show the variation encountered in these analyses.

CONCLUSIONS

As stated at the beginning two conditions must be fulfilled if mechanical analysis is to be of value in the correlation of bentonite strata: (1) samples from the same stratum must have a similar mechanical composition, (2) samples from different strata must differ in their mechanical composition. Condition 2 has been definitely proved by the work on these samples. Bentonite samples from different horizons show a great variation in the percentages of silt, clay and colloid present. Condition 1 could not be so positively demonstrated. Unfortunately bentonite seams in this area can rarely be traced for more than one half mile. The field correlation of different beds was in

many cases a long distance one. It was mainly based on the thickness of the beds and the sequence above and below, although the general location in the stratigraphic section and the color were also considered. It is strongly indicated, however, that the same seam will show similar percentages of silt, clay and colloid over considerable areas. Nos. 5, 24 and 26 gave the same size-distribution pattern. Nos. 5 and 24 are known to be from the same seam and in regard to these two samples condition 1 is satisfactorily proved. In the laboratory, tests show no. 26 to be the same as nos. 5 and 24 but that no. 25 is from a different seam. Field reports state that both nos. 25 and 26 "may be the same as nos. 5 and 24." The field reports cannot further verify the laboratory reports. These results are substantiated to some extent by the mineral assemblage since that of no. 26 agrees with nos. 5 and 24 more closely than no. 25. All other samples tested showed entirely different proportions.

A section of this shale showing the composition of the bentonites with their position in the section should be a definite aid in correlation. While entailing a great deal of time and work a stratigraphic section of this sort seems the best method of attacking the problem.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 8, NO. 3, PP. 105–111, FIGS. 1–5, DECEMBER, 1938

RAPID METHOD OF MECHANICAL ANALYSIS OF SANDS

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ABSTRACT

A new method of mechanical analysis of sands employing settling velocities has been developed especially for use aboard ship in geologic work connected with the ocean. Since coarse grains fall faster in water than fine ones, a mechanical analysis of a sample of sediment can be made by allowing the material to settle through a long column of water and observing the amounts of material which reach the bottom of the column during successive experimentally determined time intervals. A complete analysis requires about five minutes for most sands.

Among the advantages over sieving, other than saving in time and labor, are: (1) The results obtained are more closely related to conditions of deposition, since actual deposition of sand in water depends upon settling velocities rather than on mere size of grains. This is illustrated by a comparison of sieve and tube analyses of the same samples of sand. (2) Data can be taken for a continuous frequency curve by which a more complete picture of the degree of sorting can be found.

INTRODUCTION

During the present year a number of geologic problems connected with the ocean are being investigated through a project of the Geological Society of America, under the direction of Dr. F. P. Shepard, in cooperation with the Scripps Institution of Oceanography. In order to deal with the great amount of data being accumulated, it is of advantage to use special apparatus and methods, many of which have been devised especially for use at sea aboard the Institution's research vessel, E. W. SCRIPPS. In a systematic investigation of variations in grain size of sediment on the ocean floor it is of advantage to be able to make mechanical analyses of cores and other samples directly after taking them, so that critical locations for the next samples may be chosen. Too much time and labor is required by the sieve method of analysis; furthermore the necessary weighing is impractical on a boat. In addition, in investigations such as those of beach sands, which require the analysis of large suites of samples, a great deal of time is consumed if ordinary methods are used. For these purposes a settling tube, similar to that of Werner (1925), has been found useful.

APPARATUS

The equipment (fig. 1) is essentially a long glass tube having an inside diameter of 21 mm. At the bottom is a stopcock to withdraw the sample. The cock should have a bore of 6 mm to prevent jamming. On the stopcock stem, which has an inside diameter of 7 mm, is engraved a millimeter scale used to make the readings. The height from the top of the large tube to the core of the stopcock is 164 cm.

CALIBRATION

Numerous samples of quartz sand were analyzed by sieving to find the size distribution (Wentworth system) in per cent of total weight. The various size fractions were then recombined and the total sample allowed to settle through distilled water in the tube described above. All grains were started essentially together. Since large grains settle faster than small ones, the sand column accumulated at the bottom of the tube at the end of any given time interval was composed of grains larger than those still falling. The sample was allowed to settle twice. The first time, notation was made only of the total height in millimeters reached by the sample after all the sand had accumulated at the bottom. Knowing this

height it was possible to calculate the cumulative height of each size fraction, because for any size fraction the per cent of total volume (expressed here as per cent of total height) is practically the same as the per cent of total weight. The time required for each size fraction to fall was found by allowing the sample to settle in the tube a second time. In this case notation is made of the time since introduction of sample required for the sand column to reach the cumulative height of each size fraction. From timings obtained in this way the velocities of all the size fractions may be calculated. A grain assigned a certain size value may or may not have a diameter of that value, but it does have the same settling velocity as a quartz grain of that diameter.

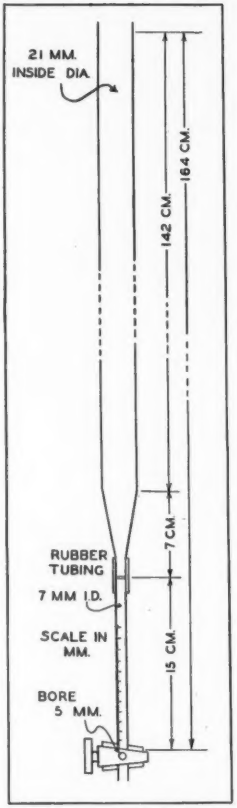

FIG. 1. Diagram showing essential features of settling tube.

Among various complications affecting the settling times are the temperature and the amount of sample. Correction for the latter was avoided by the use of samples of quartz sand of approximately equal weights. Each of twenty-three samples used in the calibration was run at several different temperatures so that differences in timing due to temperature variations could be separated from those due to other factors. This work was done, at temperatures ranging from 10°C. to 40°C., in a controlled temperature room in order to avoid convection currents which would be set up if the temperature of the water in the tube were different from that of the air outside the tube. Results of this work representing averages are shown in figs. 2–3. The variation in timing due to temperature is apparently much more pronounced for small grains than for larger ones. This is quite evidently due to the fact that the viscosity of the medium, which decreases with increasing temperature, exerts a greater influence over the fluid resistance to the passage of small grains than of large ones.

It will be noted from fig. 2 that the settling times are less, or the settling velocities are slightly greater, than those found in other investigations of coarse-grained sediments (Owens, 1911; Köhn, 1928; Richards, 1908). A satisfactory explanation of this discrepancy has not yet occurred to the writer. However, it is quite possible that it is due to the presence of a density current set up when the sample is introduced into the tube. If so the amount of discrepancy is probably related to the tube diameter, the temperature and the concentration of introduced sediment. In order to determine the exact influence of these factors, a

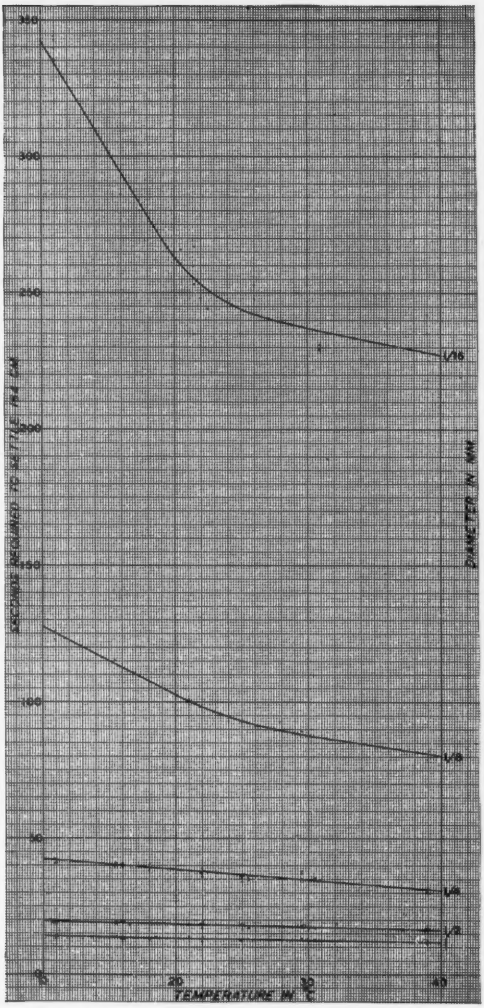

FIG. 2. Relation of settling time to temperature for quartz grains of various Wentworth diameters. Each determination is represented by a dot.

great deal of painstaking work would be necessary. Meanwhile, analyses are comparable, if each is made in the same tube using the same size of sample. Calibrated in terms of sieve sizes of quartz grains, the tube gives results comparable to those obtained by other methods.

OPERATION

In making analyses of sediments the settling tube should be filled with distilled water since tap water may cause aggregation of smaller sand grains with means of a small introducing tube. This tube is a 10 cm length of glass tubing into which about three grams of sand have been placed. The remaining space is filled with water. With the ends of the tube

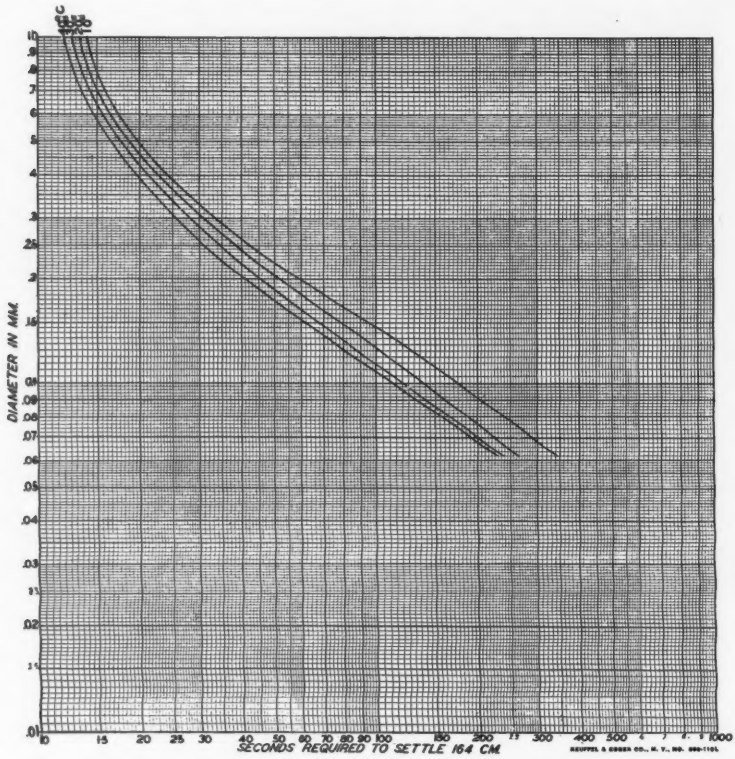

FIG. 3. Relation between the size of a grain and the time required for it to reach the bottom of the tube. Using these curves the median diameter of a sand sample may be found by noting the time required for the mid-point of the sand column to fall and reading the diameter of the sand grain which falls in that time.

consequent increase in amount of the larger sand sizes. Such aggregation may be due to the presence of a thin coating of clay particles adhering to the surface of small sand grains.

The sample in a concentrated suspension is started at the top of the column by closed by the finger tips, the sample is shaken thoroughly to detach air bubbles adhering to grains. A stop-watch is started at the same time that the suspension is released. The height of the sand on the graduated stopcock stem at the bottom of the settling tube is read at the end of

the time intervals required for quartz grains of the various Wentworth sizes to reach the bottom (fig. 2). Intermediate readings may be made in order to obtain data for a continuous sedimentation curve. Throughout the time that sand is accumulating at the bottom, the stopcock stem should be lightly tapped with a pencil, both to prevent sudden compaction of loose sand and to maintain a fairly flat top on the sand column for ease in reading the height.

Concentration, or amount of sample used, is a very complex factor influencing settling velocity, but corrections may be avoided by using samples of such size that the final height on the scale is between 40 and 70 mm. This concentration corresponds to a specific gravity of 1.008 to 1.014 for the suspension, if the sediment is considered as being equally distributed along the length of the tube. Experiments showed that the maximum variation in timing between these concentrations is less than two per cent, which agrees well with data published by Owens (1911).

Determinations of per cent weight of grain-size fractions less than 1/16 mm. in diameter are not feasible by this method. This is due chiefly to the fact that suspensions of these finer grains when introduced at the top of the tube, tend to settle as a unit. A density current is formed in which the settling velocity of individual grains plays little part. In fine grained samples the total sand percentage may be found by introducing a known weight of sample and reading the height of the sand fraction at the end of the time interval required for grains of 1/16 mm. diameter to fall. The sample is first weighed wet, as taken, and the moisture content (found in another quarter) subtracted.[1] It should not be dried for weighing, as the silt and clay fractions tend to form hard lumps which would unduly increase the sand fraction. After weighing most of the clay and silt fractions are decanted in order to prevent flocculation when the sample is allowed to settle in the tube. This may be done

[1] It might be possible to develop a simple hydrometric method of determining the total weight of a sample, thus eliminating all weighing by balance.

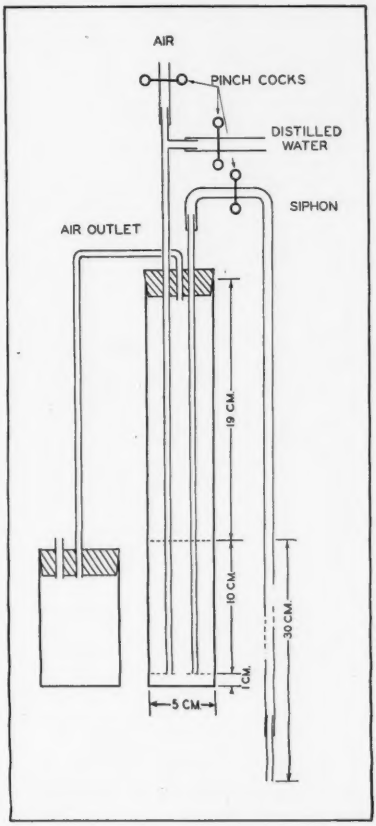

FIG. 4. Decantation tube. Water is added to a sample of sediment until the water level is 11 cm from the bottom of the tube. After a suspension is formed by air bubbling upward, it is allowed to settle for 2 minutes, the upper 10 cm is then drawn off through the siphon leaving 1 cm of suspension containing coarser grains. A clean residue of grains greater than 1/32 mm diameter is formed after 4 or 5 such decantations.

easily by means of a decantation cylinder as shown in fig. 4. A weighed quantity of sediment is placed in the cylinder, and distilled water added to a mark 11 cm from the bottom. Air under slight pressure is forced through a blower tube, breaking up the lumps of mud and suspending the particles in the distilled water. The pressure should be adjusted so that the bubbling is not so vigorous that sediment is carried through the air outlet. Five to twenty minutes is often sufficient to suspend the sediment, after which the bubbling is stopped and the sediment is allowed to settle for two minutes. The material still in suspension is drawn off through a siphon and the process is repeated. After four or five decantations very little material of diameter less than 1/32 mm remains. The residue is collected and analyzed by the method described for sands. The sand is removed from the settling tube for weighing by opening the stopcock and allowing the sand to drain into a short length of rubber tubing clamped at the lower end. Sediment of less than 1/16 mm diameter is separated by closing the cock after the sand has passed. As the weight of sand and the weight of the sediment before decantation are known, the percentage of various size groups may be calculated.

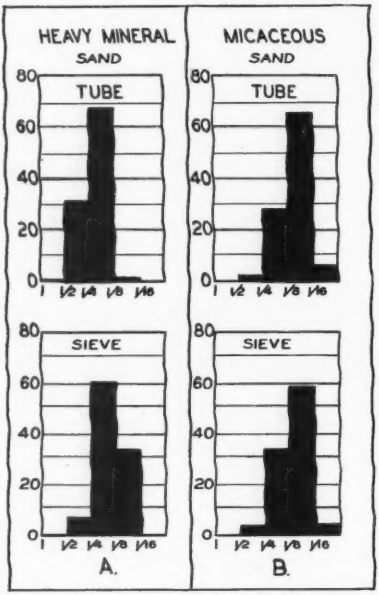

FIG. 5. A. Histograms showing a comparison of sieve and tube analyses of a heavy mineral sand. Note that the tube analysis shows the sand to have a median settling velocity equal to that of quartz grains of much larger diameter.

B. Histograms comparing sieve and tube analyses of a sand which contains a high percentage of mica. Note that the tube analysis shows the sand to have a median settling velocity equal to that of quartz grains of somewhat smaller sieve size.

In order to find the median diameter of a sample consisting only of sand, it is necessary to use only the settling time of the midpoint of the sand column. This is easily determined by interpolation if readings are taken every ten seconds in addition to the regular readings. By means of the curves in fig. 3 the median may be found without further calculation.

COMPARISON WITH SIEVING

The time required for mechanical analysis using the tube, four minutes for most sands, is much shorter than that required for sieving. Calculations require only about a minute in addition. This compares very favorably with the hours required to complete a sieve analysis.

Using the tube a continuous sedimentation curve may be obtained, by means of which information on intermediate sizes can be found. With sieves only a few points on the curve can be determined unless a greater number of screens are used than is customarily the case. The lack of completeness of the information obtained by sieving often makes it impossible to determine the exact grain size of greatest abundance. For example a well sorted sand having $\frac{1}{4}$ mm median diameter might not appear so well sorted

on being analyzed by sieving, since the $\frac{1}{4}$ mm screen would separate the sample into two size grades, each of which would comprise about fifty per cent of the total sample.

The probable error of analysis is somewhat greater than that of sieving. The maximum deviation between duplicate analyses is about three per cent as compared to about to one per cent for sieve analyses. Some skill is necessary before satisfactory results may be obtained from the tube analysis since skill is required both in the introduction of the sample and in reading the height of the sand column on the scale.

The distribution of settling velocity in a sample tells more about the conditions of deposition than does the mere particle size distribution. For example in a water laid sediment containing quartz grains of a given predominant size grade, there are often found mica flakes of a much larger sieve size, and heavy minerals of a much smaller diameter. In the tube analysis, the mica flakes settle more slowly and the heavy minerals faster than quartz grains of the same sieve size as is, in all probability, the case in actual deposition. This is illustrated in fig. 5A-B representing a sieve and a tube analysis of a heavy mineral sand and a micaceous sand respectively. It will be observed that the heavy mineral sand settles at a rate equal to that of quartz grains of a good deal larger size. In contrast, the micaceous sand behaves like quartz sand of smaller sieve size. Thus the settling tube offers a more genetic and a less statistical analysis than does sieving. This method of analysis may have further value if it is true that the settling velocity of a particle is approximately equivalent to the velocity of water necessary to move the particle in a stream (Rubey, 1933).

ACKNOWLEDGMENTS

The writer is indebted to Dr. F. P. Shepard for the original suggestion of using settling velocities as a method of mechanical analysis of sands. Appreciation is expressed to Dr. Roger Revelle for many helpful suggestions and criticism of results, and to other members of the Scripps Institution staff for their generous cooperation.

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Winterhalter's second paper (1938) summarizes, and enlarges on, most of the conclusions of the earlier one. For all except certain descriptions of technique and methods the later paper, only, need be consulted. The reviewer will consider both in the paragraphs which follow.

The author's work has been restricted to a study of the indurated sediments associated with the coal (Carboniferous) of Holland. Examination of thin sections was selected as the most promising line of attack on problems of correlation, source of materials, and others. To that end, 600 thin-sections were made from various horizons and types of sediments. Eighty photomicrographs and detailed descriptions of typical thin-sections are given in the two papers. Short characterizations of the other thin-sections are presented, by means of special abbreviations, in the proper stratigraphic position in numerous columnar sections. Some of the methods employed in this work are given below.

In a few cases thin-section mechanical analysis of sediments (following Krumbein) is given in the form of cumulative curves—curves which, however, are based on coordinates of grain size against *number of grains* (not *weight*). For the most part, however, the author is interested in the average grain size, and this statistic (and to a smaller degree the maximum and minimum grain size) plays an important rôle in Winterhalter's work. In the earlier paper the size classification of Boswell (1918) was used, and in the later paper that of Niggli (1935). Other information derived from study of the thin-sections is of various kinds: a/ percentage of quartz, b/ percentage of sericite and other interstitial material, c/ percentage of feldspar, d/ mode of cementation or induration, e/ presence or absence of rock particles, and other, miscellaneous data. All of this information, in very condensed form, is put beside the columnar section, and correlations are then made. Some of the main conclusions are: 1/ the large divisions of the Dutch Carboniferous are different in their lithologic character, but the characters of any one bed are repeated again and again in the column; therefore, one cannot determine stratigraphic position by one observation (thin-section). 2/ lithologic horizons can be traced widely over the whole coal basin. 3/ some of the sediments are well graded; others are not. The first type possibly was laid down during times of "orogenic quiet," and the second during orogenic movement. 4/ the fact that the sediments coarsen in many directions makes it impossible to trace them to their source, or sources.

The reviewer believes that there is one drawback to this type of work: it is very difficult to tell whether or not the results are justified by the data. Such checking would involve painstaking examination of all the columnar sections, comparison of all the abbreviated information on lithology, and the making of a series of curves, charts, or other figures suited to rapid visual inspection, or to numerical treatment. Perhaps Evans' "range tables" could be adapted to such investigations. However, these strictures should not reflect on Winterhalter's results, which have clearly involved months of careful and detailed laboratory work.

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Bryn Mawr College

Text Book of Petrology, Vol. I, The Petrology of Igneous Rocks, F. H. Hatch and A. K. Wells, 9th edition, pp. i-xx, 1–368, Figs. 1–154. *Vol. II*, The Petrology of Sedimentary Rocks by F. H. Hatch and R. H. Rastall, revised by Morris Black, pp. 1–383, Figs. 1–75, published by George Allen and Unwin, Ltd., London. American representative, Macmillan Company, New York.

These two works are companion volumes in which all varieties of rocks are considered except the metamorphic equivalents of the sedimentary rocks.

Volume I, or The Petrology of the Igneous Rocks, is divided into five parts which are as follows: (1) origin, occurrence and external structures of the igneous rocks; (2) constituent minerals of the igneous rocks; (3) consolidation of magmas and the textures that result therefrom; (4) classification of igneous rocks; (5) and origins and associations.

Most of Part I is devoted to modes of occurrence of igneous rocks. These are divided into three classes: (1) subjacent which includes batholiths, domes, stocks, and bosses; (2) discordant injections consisting of dikes, veins, apophyses, tongues, ring-dikes, cone-sheets, bysmaliths, plugs and necks; and (3) concordant injections which consist of laccoliths, phacoliths, sills, lava flows, and tuffs. External structures are classified as joint and sheet, platy, columnar, flow, and vesicular structures; and pipe amygdules.

Part II treats of the constituent minerals of igneous rocks. Minerals are classified as primary and secondary; the former divided into essential and accessory. The appearances of minerals under the microscope are described and most of the chapter is devoted to descriptions of the rock-forming minerals. These are placed in 21 divisions.

Part III considers consolidation of magmas and the textures that result from consolidation. Sixteen varieties of textures are described.

Classification of igneous rocks is treated in Part IV. Seven divisions are made which are termed granite, syenite, diorite, monzonite and gabbro clans and ultra-mafic and pyroclastic rocks. This chapter is the largest division of the book.

Part V discusses the origin of rock types, igneous rock assemblages and the cycles of igneous activity in the British Isles.

Illustrations for the book are largely drawn from the British Isles. There is a good index of localities and a fairly good general index, list of general reference rocks is given, and in addition there are many footnotes.

This work on the igneous rocks is easy reading and constitutes an excellent work of reference for students interested in this division of rocks. The reviewer considers that the book would serve as an excellent text for a course in igneous petrology. The method of classification may not recommend itself to everyone but this possible defect is inherent in most, if not all, classifications of rocks which are rarely satisfactory to any other than their makers.

Volume II, The Petrology of Sedimentary Rocks, is a book that should be on the working desk of every student of sediments but many readers will be disappointed with the brevity of treatment. The book contains 17 chapters, each covering approximately the same number of pages, and treatment of many subjects is brief. To consider the contents of the book in detail would extend to great lengths, so one must be contented in merely naming the chapters with brief comments.

The book is far too brief for the subject matter. The treatment of origin and transportation of sedimentary materials is very elementary and incomplete and this statement may be made for other parts of the work. Bare mention is made of manganese in sediments and almost as much of barium, less of copper, and

nothing of strontium, sulphur and orthogenic feldspar.

Chapter I, the introduction, considers briefly the environments of deposition and the influence of climate. Environments of deposition are classified as continental, intermediate, and marine. Only a little more than two pages are devoted to this important subject.

Chapter II discusses the origin and classification of sedimentary deposits. Sedimentary rocks are classified as fragmental, chemical, organic, pyroclastic, and residual. Most of this short chapter is devoted to origin and transportation of sedimentary materials and less than three pages to classification.

An introduction to fragmental deposits is considered in Chapter III. Methods of study, classification, and presentation of results are given.

Chapters IV, V, and VI treat respectively of rudaceous deposits or the larger clastics; arenaceous deposits or the sands; and argillaceous deposits or the finer-grained clastics.

Iron-bearing deposits are considered in Chapter VII. Chapters VIII and IX discuss the calcareous deposits in the two divisions of limestones composed of calcite and limestones of which a part is dolomite.

Chapter X considers siliceous deposits which are divided into the two kinds of organic and diagenetic silica. The authors seem to be of the opinion that silica does not originate as a primary deposit.

The various evaporites are considered in Chapter XI and Chapter XII treats of the carbonaceous deposits. Chapters XIII and XIV, both short chapters, treat of phosphatic deposits and pyroclastic deposits.

Chapter XV returns to the problem of environment with consideration limited to the marine environment, and the various phases of marine deposition are considered. Diagenesis and related processes are considered in Chapter XVI, and in Chapter XVII weathering processes and the formation of residual deposits and soils are discussed.

The work has a good index and there is a classified bibliography covering 7 pages and a bibliography of 21 pages arranged according to authors. Illustrations are ample and an appendix gives the characters of common minerals occurring in detrital sediments.

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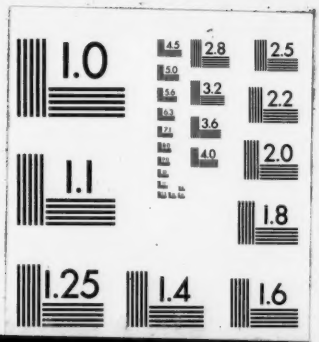
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